MODELLING AND EXPERIMENTAL STUDY OF GRANULAR MATERIAL DRYING IN A VIBRATED FLUIDIZED BED

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Abstract.

Experimental results and drying characteristics of a continuous vibrated fluidized bed are presented and discussed. Air temperature and flow rate, solid flow, amplitude and frequency of vibration were the studied variables. Moisture content and temperature of the solid in different positions along the vibrated bed were obtained to establish drying dynamics of the process.

The experimental results were compared with a simulation model based on the application of mass and energy balances to the air and solid in a differential volume of dryer. The drying rate was calculated in terms of a heat transfer coefficient between the air and the solids, considering the constant rate period and the linear falling-rate period, with unsaturated surface drying assumed proportional to the free moisture content of the solid.

The comparison between the experimental values for the moisture content and the temperature of solid with those predicted by simulation model developed showed a reasonable agreement.

Keywords*: Modeling drying, Vibrated Fluidized bed dryer;.*

Introduction.

In the last decade the conventional technologies of drying have experienced a permanent revision to satisfy growing requirements of quality and greater production rate, compatible with a better use of the caloric energy and a reduction of environmental contamination. In this aspect, the introduction of new technologies and the use of different drying modes have meant the gradual

replacement of conventional dryers like the direct rotary, the fluidized bed and the spray driers. For example, in Chile, the different processes of fish meal production, replaced the direct rotary drier by indirect steam-tube rotary drier, which exhibit higher energy efficiency and low environmental impact. The fish meals quality was increased but the low drying rate reduced the total production of this equipment.

The fluidized bed dryers with internal heat exchangers, which are easy to control, constitute an interesting alternative and provide low retention times. This equipment shows a better heat transfer efficiency compared to the traditional fluidized bed dryer. Fouling problems, handling of sticky materials, dragging of fine solids and agglomerated particles, have contributed in the last decade to the introduction of the vibration, in addition to the traditional air fluidization of particles bed (vibrate fluidized bed). The vibrate fluidized bed has a wide application in the chemical industry, foods processing, mining process, plastics, in a laboratory level as well as at pilot plants (Gan , 1989; Shah and Goyel, 1995). In this combined drying ways, low air rate can be used, reducing blower power and energy consumption, size of ducts and blow out of particles, providing a better product quality together with a higher control of the residence time. Particularly, for agglomerating and sticky materials with high moisture contents (case of fish meal and similar), the heat and mass transfer rate are higher compared to fluidization only. Mechanic vibration not only favored fluidization but also permitted to process moist material at lower velocities than in the conventional fluidized bed (Vanecek et al., 1966). For this type of solids, existing publications focus mainly on technological aspects while a study on fundamental aspects of vibrate-fluidized drying is scarce. Most of these publications have been originated in the oriental Europe (Russia, Poland), as well as in China and Japan, and the access to them is limited. At the present time, it is more often found that fluidized bed dryers are built provided with vibration (Mujumdar, 1991), which indicates the importance of this combined mode of drying.

Extensive research has been carried out on fluid dynamic aspects of vibrate-fluidized bed which give a large number of references; however, they are basically studies about the gas flow rate, pressure drop in the bed and the minimum velocity of

vibrated fluidization. In this work, the emphasis is centered in drying and its modeling based on heat and mass transfer coefficients between the gas and the particles, as a function of the vibration variables. The application of this process has been developed for materials difficult to fluidize like big particles, suspensions and pastas, where the airflow required is controlled by the demand of the fluidization process and not for the heating required by the drying process. In this sense, all the available information is of technological type restricted to the particular solid utilized. Esdèz and Ormòs (1984), Danielson and Hovmand (1980), Pakowski et al. (1984), Kuipers et. al (1996), show experimental data for drying particles like magnesium chlorate, polyethylene, caffeine, pharmaceutical products, potato starch, under different types of vibrate-fluidized bed dryers, concluding that an optimum value of the vibration parameter exists coirresponding to highest drying rate, but they did not study the basic phenomenon of heat and mass transfer. Choc (1975) studied the mass transfer through their analogy with heat transfer, using spherical particles of PVC and naphthalene. Mushtayev et al. (1972) informed mass transfer coefficients for PVC spheres and benzoic acid, as a function of the vibration parameter and bed characteristics. Garin et al. (1994) studied the mass transfer in naphthalene-air system and established a correlation for the transfer coefficient as a function of the amplitude and frequency vibration, which showed a maximum for one value give of the vibration parameter (Aw^2/g), depending of the air velocity. Recently, Moreno et.al. (2000) summarizes results concerning hydrodynamics and drying of sawdust dryer in a vibrating bed, but the dryer behavior has been analyzed in a global way. Ray M. S. (1996) informed a bibliographical revision that included the 40 most important chemical engineering journals from the year 1980 at 1993, have more than enough theory and design of drying operations, finding scarce works on drying in VBF, mainly in analysis of fundamentals mass transfer during the drying and development of characteristic models of the periods of constant and falling rate.

One of the most important works related with the objective of the present papers is the informed for Borde et al. (1997) on theoretical and experimental study of drying in a dryer of VFB, applying models of phenomenons of transfer of heat and matter in the analysis of their results, so much for the period of constant rate as the falling one. The used granular material was sand, classified as type B for Geldart.

Their model of correlation of the coefficient of transfer of heat in function of the number of Reynold includes the factor vibracional Fv and the number of Arquímedes.

The objective of the present work is to present the results of drying corn grits in a continuous vibrate-fluidized bed drier, under different vibration conditions, in terms of the heat transfer coefficients between the air and the solid bed. A simulation model of the drying process is also presented, based in the application of the mass and energy balances applied to a differential element of dryer.

Mathematical formulation of a model.

It is considered an element of differential dryer volume of length ΔZ , width W and thickness e, as shown in Figure 1.

The mass and energy balance equations consider the following assumptions,

- Stationary state.
- Plug flow for solid movement at a constant velocity $V_s = L/\theta_R$, where θ_R is the retention time for the solid.
- Heat loss by natural convection it is considered from the rectangular camera of the vibrated bed dryer to the atmosphere.

The gas and solid enthalpies, on dry weight basis, are given by:

$$H_G = \left(C_B + Y\,C_A\right)\left(T_G - T_O\right) + \lambda_O Y \tag{1}$$

$$H_S = \left(C_S + X\,C_{AL}\right)\left(T_S - T_O\right) \tag{2}$$

According to the assumptions stated above, the equations of mass and energy balances applied to the volume element of solid and gas can be summarized as:

Mass balance to the solid

$$\frac{dX}{dZ} = -\frac{N}{V_S} \tag{3}$$

where N is the drying rate, defined as the evaporated solid moisture per unit of time and dry solid weight.

Mass balance to the gas $$Y - Y_e = \frac{S_S}{G_B^{'}} \frac{dX}{dZ} \qquad (4)$$

where G'_B is the dry air flow per unit of dryer length.

Energy balance to the gas:

$$G'_B\,(H_G - H_{Ge}) = \frac{NS_S}{V_S}(\,C_A\,T_S + \lambda_O\,) + Q'_P - h\,A'(T_G - T_S) \qquad (5)$$

Energy balance to the solid:

$$\frac{dT_S}{dZ} = \frac{1}{S_S\,(C_S + X\,C_{AL})}[h\,A'(T_G - T_S) \quad - S_S\,\frac{N}{V_S}\lambda_S\,] \qquad (6)$$

where Q'_P = heat lost to the environment for unit of dryer length.

Drying rate, N. In this work, it is considered that the drying rate, N, exhibits a period of constant regime, of saturated surface, and a falling period where the drying rate falls proportional to the free moisture content, which can be expressed (according to Shene *et al*, 1996) as:

$$N = \frac{h\,A'}{S_S\,C_H} V_S (Y_S - Y)\,F(X) \qquad (7)$$

With $$F(X) = \frac{X - X^*}{X_C - X^*} \qquad (8)$$

where X_C and X* represent the critical moisture and the equilibrium moisture of the solid, on dry weight basis.

For the constant period: $X \geq X_C$, $F(X) = 1$

Gas-solid heat transfer coefficient, h. The slopes of the experimental curve of solid moisture content X vs Z, during the constant regime period, allow to determine the constant drying rate N_c. The heat transfer coefficient between the gas and the solid was calculated using this value of N_c, according to the following expression:

$$h = \frac{S_S}{V_S} \frac{N_C \lambda_S}{A^{'}\left(T_G - T_W\right)_{ML}} \tag{9}$$

where $(T_G\text{-}T_W)_{ML}$ is the mean logarithmic difference between the dry air temperature and the wet bulb temperature at the inlet and outlet of the bed.

It can be demonstrated that:

$$N_C = -\frac{dX}{dZ} V_S \tag{10}$$

$$V_S = \frac{S_S}{\rho_L \, e \, W} \tag{11}$$

$$A^{'} = \frac{6}{\phi \, d_P \, \rho_S} \frac{S_S}{V_S} \tag{12}$$

Equipment, materials and experimental methodology.

Figure 2 is a schematic representation of the equipment used in the experimental work. The vibrate-fluidized bed dryer is constituted of a rectangular chamber with a 1 m x 0,35 m cross-section and 0,1 m height. Air was supplied to the bed through a perforated steel plate (air distributor), by a 5,5 HP centrifugal blower.

The vibrate-fluidized chamber was mounted on four springs located in the corners, which was vibrated in the vertical plane (amplitude) by means of a variable drive mechanism, connected to a 1 HP motor provided with a frequency regulator. The solid was continually fed and its flow was regulated by means of a rotational valve moved by a 0,25 HP motor provided with a rotational speed regulator between 5 and 30 rpm. The drying air was heated by mixing with combustion gases.

The drying material was corn grits from the production of corn flour, supplied by Moliner Corporation, The particle sizes were between 10 and 4 Tyler mesh. Its initial moisture content was conditioned by water pulverization to a value between 30 and 40%, dry weight basis, and maintained 24 hours in a refrigerated chamber. The physical properties of the solid are given in Table 1.

The methodology consisted on measuring the temperature and moisture content of the solid and gas, once the stationary state was reached, for each group of operating conditions in terms of air temperature and flow rate, solid flow, amplitude and frequency of vibration were the studied variables. The solid and air temperatures were determined by means of thermocouples located inside the camera, the solid moisture content was determined on samples drawn by means of a collector device introduced through an opening in the chamber door. The convective heat lost Q'_P was calculated by measuring the wall temperature at different positions of the external surface of the drying chamber

Results and discussion.

The operational parameters for the different experimental run could not be selected in independent form, due to the sized and design of the drier. The obtained values correspond to operation conditions where the process operated in stationary state, in this condition the variables or parameter measures could be reproduced, minimising the experimental error.

A summary of the main experimental data and obtained results of all experiences is given in Table 2. Figures 3, 4, 5 and 6 show the profiles of solid moisture and temperature for some experimental runs.

It was observed that all drying exhibited two periods, with values of critical moisture content between 0,2 and 0,12 obtained among the positions 0,3 and 0,45 m from the bed inlet. The wet-bulb temperature of the air fluctuated between 32ºC and 36ºC, and the solid temperature varied accordingly in the same range.

The drying rate obtained for the constant rate period, calculated from Equation 10 with the slopes of figures 3 and 5, increased with the vibration, velocity and temperature of the air. Table 2 shows the heat transfer coefficient calculated according to the Equation (9), and it is observed that they vary between 2 and 30 $W/m^{2o}K$. It is interesting to note that all the values for the heat transfer coefficient are lower than those for a fluidized bed, calculated according to equations given in Kunii (1991).

For the drying process simulation, the differential equations were solved using the software Matlab. The heat transfer coefficients were directly used, since it was

not possible to obtain a correlation in terms of dimensionless parameters. Bibliographic data were used for the physical properties and other necessary parameters. Both, the equilibrium moisture content and the particle sphericity showed a great influence in the simulation results. An increase in the equilibrium moisture content decreases the moisture and temperature of the solid, while an increase of the mean particle sphericity of the bed tends to decrease the heat transfer coefficient and therefore the drying rate. For the simulation, it was assumed a value for sphericity of 0,75 (from Rossi, 1980). The curves in figures 3, 4, 5 and 6 show good agreement between the experimental values and the predicted results.

Conclusions.

The continuous operation of a vibrate-fluidized bed dryer was modeled and simulated using a drying model proportional to the free solid moisture, with a deviation lower than 5% in the predicted values.

In order to extend the applications of this model, it is recommended to test it under larger variations of the vibration factor Aw^2/g.

Nomenclature

A	amplitude	m
A'	transfer area per unit length	m
C	specific heat	J/Kg ºK
d_P	average diameter of the solid	m
e	bed thickness	m
f	vibration frequency	hz
g	gravity acceleration	m/s
G_B	dry air flow	Kg /s
G'_B	dry air flow	Kg/s m

H enthalpy J/Kg

h heat transfer coefficient J/s m ºK

k thermal conductivity of the air J/s m °K

L dryer length m

N drying velocity 1/s

N Nusselt number = h d_p / k ----

u

Q losses of heat to the atmosphere for unit of length J/s m

´P

R Reynolds number = $d_p v_g \rho / \mu$ ----

e

S flow of dry solid Kg /s

s

T temperature ºK

V velocity m /s

V velocity of solid m / s

s

W wide of bed m

X solid moisture

Y air humidity

Z bed position m

Greek letters

λ latent heat of water vaporization J Kg^{-1}

ρ density Kg m^{-3}

ϕ particles sphericity ----

ω angular velocity s^{-1}

μ air viscosity $Kgm^{-1}s^{-1}$

θ residence time s^{-1}

R

λ latent heat of water vaporization J Kg^{-1}

* equilibrium

A moisture

B dry gas

c critic

e entrance

G gas

H moisture

L bed

o reference level

S solid

w water

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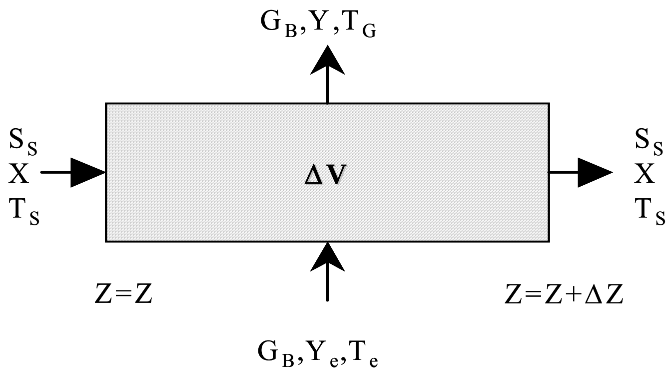


Figures 1. Differential element

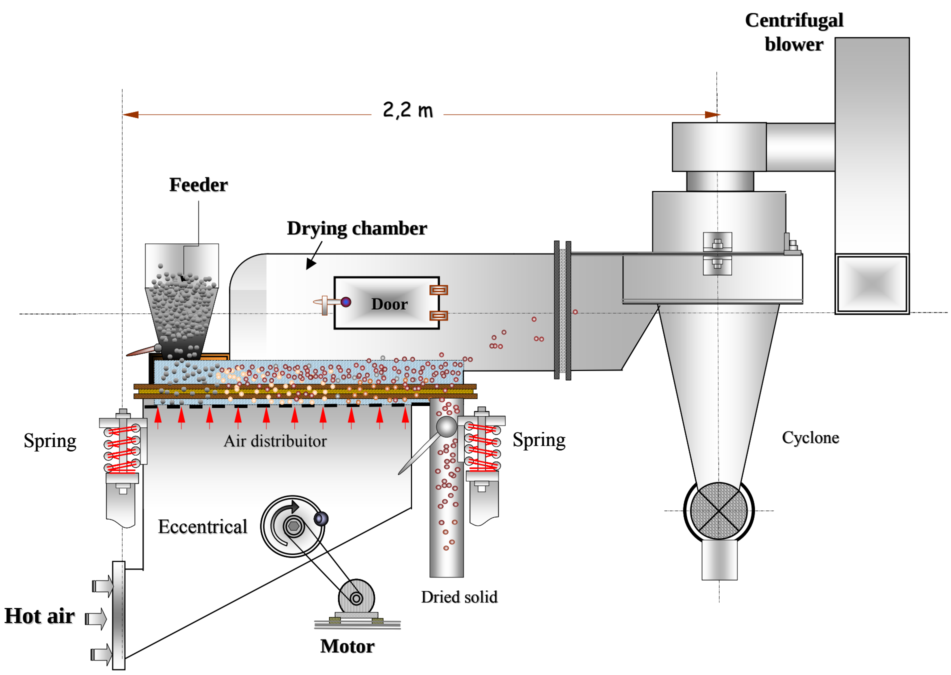
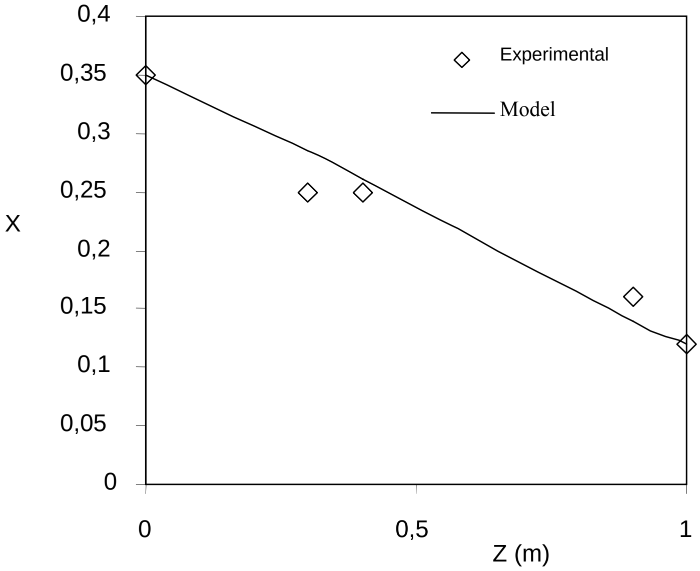


Figure 2. Schematic diagram of experimental equipment.



Figures 3. Moisture content variation of solid along the bed for Ss = 30,7 kg/h, A= 25 mm, f=20 Hz, T_{Ge}=107 ºC, and e = 2,5 cm, Xc=0,2 b.s.

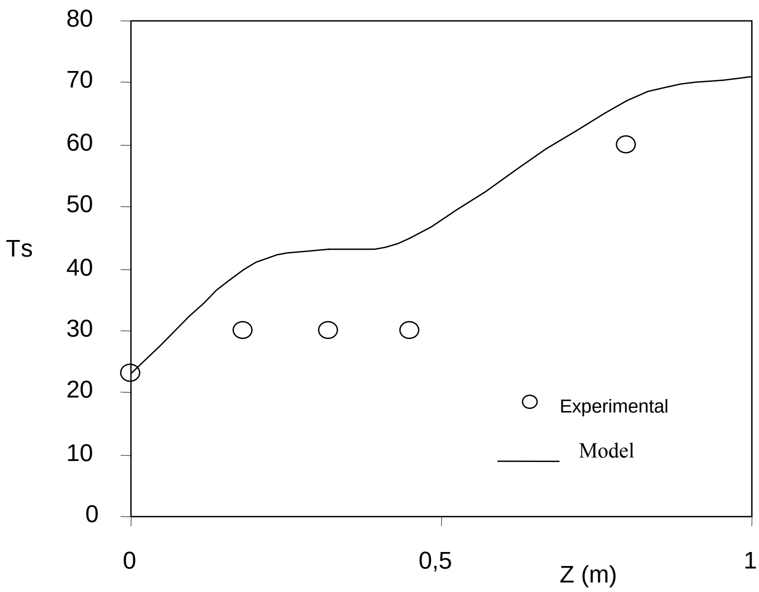


Figure 4. Solid temperature variation along the bed for Ss = 30,7 kg/h, A = 25 mm, f=20 Hz, T_{Ge}=107 ºC, e=2,5 cm, Xc=0,2 b.s.

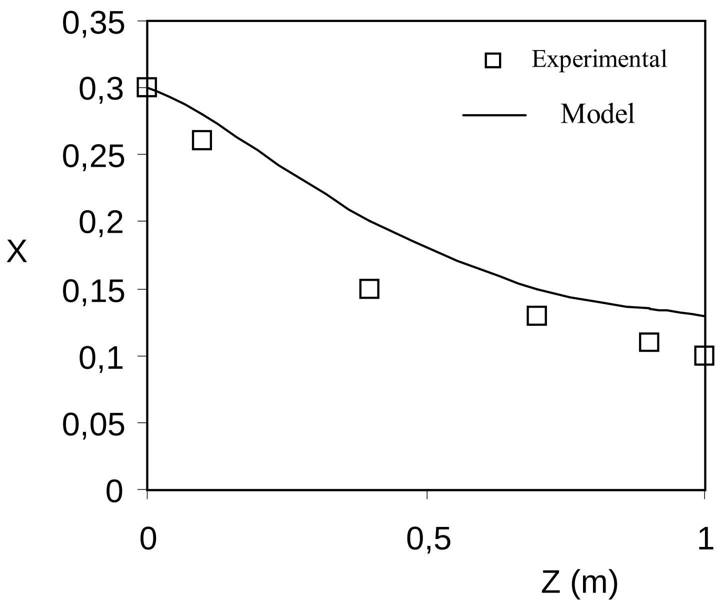


Figure 5. Solid moisture variation along the bed for Ss=40,7 kg/h, A = 30 mm, f = 40Hz, T_{Ge} = 95 ºC, and e = 0,5 cm, Xc=0,18 b.s.

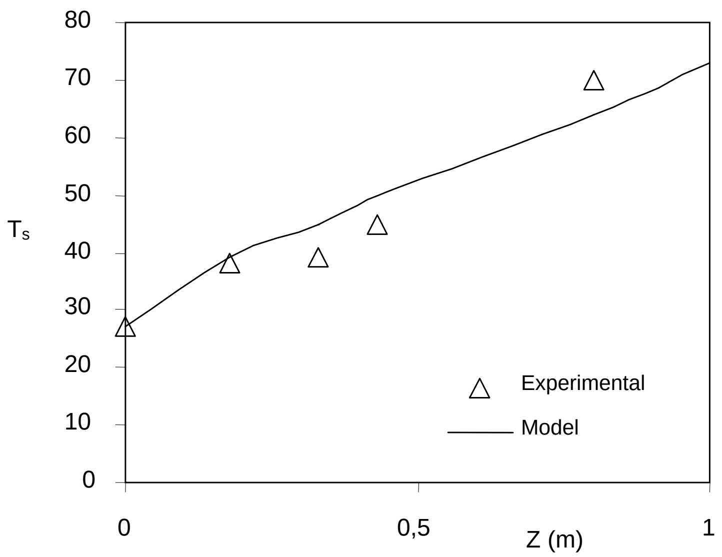


Figure 6. Solid temperature variation along the bed for Ss = 40,7 kg/h, A = 3,0 mm, f = 40 Hz, T_{Ge} = 95 ºC, and = 0,5 cm, Xc = 0,18 b.s.

Table 1. Physical properties of the grits of corn.

Average diameter, m	0,0017
Solid density, kg/m^3	1043
Apparent density, kg/m^3	686
Porosity of the bed	0,66
Sphericity	0,75
Specific heat, J/kg ºK	1170

Table 2. Experimental data and results

T_{Ge}	X_e	V_G	10^3 S_S	10^3 A	f	e	10^3 N_c	h
107	0,35	0,36	8,5	2,5	20,0	0,025	0,61	7,4
102	0,35	0,36	5,8	2,5	19,7	0,025	0,47	5,5
104	0,35	0,36	17,3	2,5	19,1	0,015	1,48	17,2
96	0,39	0,90	3,3	2,5	19,5	0,020	0,68	8,4
99	0,41	0,90	4,5	2,5	19,0	0,020	0,65	7,6
80	0,30	0,90	5,0	3,0	22,0	0,030	0,12	2,0
97	0,30	0,90	15,3	1,5	18,0	0,030	0,28	4,3
80	0,30	0,95	16,7	3,0	40,0	0,050	1,87	30,2
95	0,30	O,95	11,1	3,0	40,0	0,050	1,55	21,6